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Co-Design and Experimentation of a Prototype of Agroecological Micro-Farm Meeting the Objectives Set by Climate-Smart Agriculture

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Abstract: Developing climate-smart agriculture is an urgent necessity to ensure the food security of a growing global population, to improve the adaptation of agricultural systems to climatic hazards, and to reach a negative carbon balance. Different approaches are being explored to achieve those objectives, including the development of new technologies for efficiency improvements to current systems and substitution of chemical inputs by bio-inputs, but the urgency of the climatic, social, and environmental context calls for more disruptive actions to be taken. We propose an approach to the design of climate-smart production systems structured in four steps: (1) diagnosis of the study region on the basis of the three pillars of climate-smart agriculture, (2) co-design of a disruptive system only based on agroecological and bioeconomic principles, (3) long-term experimentation of this system, and (4) in itinere adjustment of the system based on collected data and on-field evaluations with agricultural stakeholders. The outcome of this approach is the agroecological microfarm named KARUSMART, settled in 2018 on one hectare in the North Basse-Terre region of Guadeloupe (F.W.I.). This study presents its co-design and experimentation stages as well as the first performance results. At the end of the first two years, this microfarm showed a clear improvement in 15 of the 19 indicators used to evaluate the performance of the actual farming systems in the study region. Among the most striking results are a clear superiority in nutritional performance from 3 pers.ha^{-1} to 8 pers.ha^{-1} and a reduction in GHG balance from +2.4 tCO_{2eq}.ha^{-1} to -1.1 tCO_{2eq}.ha^{-1} for the study area and the microfarm, respectively. These results are promising for developing climate-smart agricultural systems and need to be consolidated further through longer-term monitoring data, the implementation of more similar systems in the study area, and the implementation of the design principles in other contexts.

Keywords: agroecology; pilot farm; climate-smart agriculture; food security; adaptation; mitigation; microfarm

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1. Introduction

1.1. The Urgent Need for an Agroecological Transition

Since the 1960s, ecological findings related to food chain functioning have urged societies to revisit both their human place and strategies for food production, transformation and distribution processes [1,2], which has been subsequently formalized in the sustainability concept [3,4]. The finitude and nonrenewable characteristics (the nonrenewable characteristic of resources depends on the way they are used/recycled) of most of the earth's resources (soil, water, phosphorus), the importance and weakness of particular ecosystem services (pollinators, water, and air purification), and the externalities on human health and the economy have become central in the strategic thinking of future agricultural systems. During the same period, climate change emerged as a prominent and urgent international scientific and policy issue initiated by the First World Climate Conference in

1979 in Geneva [5]. Three decades later, the need for developing climate-smart agriculture (CSA) was developed by the the FAO [6] and emphasized in numerous studies. All these issues are stressed by a rising population expected to increase from 7.7 billion in 2019 to 11.2 billion by the end of the century [7] and constant global gross domestic product growth (3.7% in 2018) [8].

Strategies for achieving better sustainability of agricultural systems have relied on three research axes: (1) improving the efficiency of actual systems, (2) replacing conventional inputs and practices with eco-friendly alternatives, and (3) redesigning agroecosystems using ecosystem functions and services as the foundation. These three axes are referred to as the "Efficiency," "Substitution," and "Redesign" approaches, respectively, within the scientific literature [9–11]. Numerous researchers agree with the fact that redesigning farming systems based on agroecology is now a central approach to investigate in order to respond to contemporary issues while improving food sovereignty, control at the local level, and social justice [12]. Replacing external inputs with onsite or local ecosystem services and mostly relying on high diversity, agroecology contributes to food and health sovereignty [13,14]. Replacing external inputs with shared resources and local knowledge also contributes to social justice, cultural development, and resilience at the community and global levels [15,16].

Agroecology proposes a systemic approach for the integration of ecosystem functions and services by applying ecological concepts and principles [17,18] that could also help develop climate-smart agriculture [19,20].

Although this science represents one of the first principles of agriculture [21], the term became useful since the green revolution to describe research axes mainly relying on also specific agroecological practices, as well as a citizens' movement striving for rural development, environmental improvement, farmers' autonomy and food sovereignty [13,22]. Nevertheless, as stated in [23], agricultural sustainability does not mean ruling out technologies or practices on ideological grounds, provided they improve productivity without harming the environment. Thus, agroecology should be a paradigm guiding research but not an ideology locking out other opportunities and innovations. This point is important since, in the field of agroecology, ideological positions and societal projections take a non-negligible place and lead to contradictory debates [22,24–26].

Norder et al. [27] wrote that "the discussion of the [. . .] importance of controversies in the relationship between science and society must also address positions, such as the one held by Sevilla-Guzman and Woodgate [28], who defend the "indivisibility of science, social movements and practice, without which agroecology would be an instrument at the service of capitalism." This position was supported by different studies and tended to orient agroecological research in such a way that local contexts and social expectations are necessary drivers for the transition [29,30]. Based on these assumptions, two additional upper levels of research axes that go beyond the farm are required, in addition to the "Efficiency," "Substitution," and "Redesign" approaches, including: (1) to re-establish a more direct connection between those who grow our food and those who consume it; and (2) to build a new global food system based on equity, participation, democracy, and justice [31].

In this context, agroecology also presents advantages as it tends to foster community support and local knowledge but also to facilitate the development of a sustainable bioeconomy [32]. In this sense, the objective of this study was not to propose climate-smart practices or production systems that could be adopted within the current food system but to design, experiment, and assess a climate-smart production system that could form the basis of a new food system at a regional scale. The assumption was that in the way of scaling up agroecology, a concrete implication of local research institutes in the food system is needed, with research programs adapted to the specificity of the regional context and involving local citizens and decision-makers.

1.2. Pilot Agroecological "Microfarms" as a Stepping Stone?

Globally, 84% of farms are less than 2 Ha (12% of farmland) and contribute to 20% of food consumed, and 98% of farms are less than 20 Ha and contribute to 51% of food consumed in low- and middle-income countries (from a subset of 460 million farms in 161 countries). However, those small- and medium-scale farms only use 30% of the total farmland [33]. Small farmers can attribute this inverse relationship between farm size and output to the more efficient use of land, water, biodiversity, and other agricultural resources. Therefore, in terms of converting inputs into outputs, society is better off with small-scale farmers [13,34].

According to Morel and Léger [35], the term "microfarm" was termed in industrialized countries to characterize small-scale farms responding to five different criteria: (1) cultivated acreage is smaller than official recommendations (typically less than 1.5 Ha); (2) commercialization strategies include community-oriented marketing through short supply chains; (3) a wide diversity of plants is cultivated; (4) management relies on a low level of motorization and investment; and (5) the farmer gives as much importance to ecosystem health and social welfare as maximizing their income.

Based on these five criteria, we assumed that "microfarms" could be a promising agricultural model for the redesign of production systems based on agroecology. To this end, there is a need for research institutes to contribute more to their design and their assessment through data collection, first on experimental farms and then on pilot farms implemented in the study region. Moreover, the involvement of different stakeholders in the design and assessment processes is necessary to achieve diversified sources of information, balancing the lack of data for these radical agroecological systems; but also obtain an agroecological microfarm that takes into account multi-dimensional and multi-scales goals, as well as adoption constraints and societal projection of agriculture in the study region.

1.3. Objectives of the Methodology

There is a twofold issue regarding agroecological microfarms (AEMFs): (1) what is their capacity to meet the three objectives of climate-smart agriculture [6] and (2) how to create the economic, institutional, and social environment to develop AEMFs in a given region? To answer these questions, robust scientific evidence is needed to urge a potential "AEMF scaling up policy" in a specific regional and cultural context. To this end, one of the first necessary steps is to obtain robust scientific data about these systems and develop case studies and long-term data acquisition.

To overcome this situation but also other "lock-in" effects in the transition of current agricultural systems [36], the present paper describes an original framework carried out for the codesign and the experimentation of an AEMF aiming for the potential development of a CSA in the North Basse-Terre region of the Guadeloupean archipelago (F.W.I.). The aim was to develop and apply a methodology uniting three objectives: (1) to design a prototype of AEMF tailored to the specificity of the studied region, (2) to initiate the techno-economic and agronomic data acquisition produced through an experimental AEMF, and (3) to produce an assessment of the AEMF after two first years of experimentation based on a set of indicators of climate-smart agriculture (CSA). The overall purpose of this study was not the design of a farm that could be adopted in the current food system but the design of a prototype that could support the transition toward a new food system responding to high goals in terms of sustainability and climate-smart agriculture development in the region.

2. Materials and Methods

2.1. Study Site

The study was conducted in Guadeloupe, a French Overseas Department of the West Indies (in the Caribbean, latitude 16°13′ N, longitude 61°34′ W). Guadeloupe is an archipelago (1628 km^2) comprising two main islands, Basse-Terre (848 km^2) and Grande-Terre (586 km^2), with strong ecological contrast. Sierra et al. (2015) [37] divided the archipelago of Guadeloupe into five agroecological regions (AER). This study focused on the agroecological region of the north of Basse-Terre (NBT), which is characterized by an annual mean temperature and rainfall of 25.4 °C and 2300 mm.yr^{-1}, respectively, and kaolinitic ferralsols developed on old volcanic ash deposits. The agricultural land area (ALA) represented 5033 ha and 849 farms (16% of the ALA and 18% of the farms of the whole archipelago, respectively), with an average farm acreage of 5.9 ha and 1.2 ha for the fields.

The AEMF experimented covered an area of 0.7 ha at the research institute of Duclos (Institut national de recherche pour l'agriculture, l'alimentation et l'environnement, INRAE) in the NBT region.

2.2. Overview

The present study reports the outcomes obtained from steps 3 and 4 of the 5 steps global methodology explained explained as follows:

- Step 1: Diagnosis through a typology of the farming system and the survey of a representative sample of farms in the study region. This first step aims at characterizing the farming system of a specific AER to carry out a survey of a representative sample of farmers. This characterization corresponds to the typology of the farms. The 2010 governmental farmers' declaration data of areas and crop rotations of 849 farms (methodology described in Todoroff, Gibon, and Abrassart [38]) were used as input data to build up the typology. We obtained a 4-class typology following the method detailed in [39], combining principal component analysis with hierarchical clustering. From the typology, three farms in each of the four clusters obtained, i.e., 12 farms, were randomly selected and surveyed. This survey aimed to collect data for (1) characterizing the input and output flow of the farm processes, (2) characterizing the biophysical environment of the farm, (3) guiding the selection of a set of indicators used in step 2, and (4) initiating a close link with farmers to involve them in the co-design of the AEMF.
- Step 2: The assessment of the farming system. The second step is the assessment of the regional farming system based on a set of indicators measuring the performances related to the three pillars of CSA (food security, adaptation, and mitigation). During successive transdisciplinary workshops involving researchers, farmers, and decision-makers, a set of 19 indicators were selected (Table S1). Those indicators were selected in such a way as to be as generic as possible by taking into account the local context in order to have a common base when comparing production systems from other AER or other countries. The survey of the 12 farmers helped select indicators adapted to available data, but in some cases, gray and peer-reviewed literature was needed. The 19 indicators provided measures assessing the performance of the four types of farms with regard to CSA's three pillars. Both steps 1 and 2 were detailed in Supplementary Materials.
- Step 3: Designing the prototype of AEMF. This step corresponds to the "de novo" co-design of the prototype of AEMF based on agroecological (AE) principles/practices and opportunities for a circular bioeconomy at the regional scale. Co-design proceeded during interdisciplinary workshops involving agronomists, economists, ecologists, technicians, farmers, and decision-makers (Figure 1). A referent group proposed an initial conceptual model that was discussed and modified by a larger transdisciplinary working group; then, the new conceptual model was ex-ante assessed with the set of indicators built during step 2 and with data based on the literature and professional expertise. The results of the assessment were used to feed the next transdisciplinary working group until the prototype was validated for experimentation.
- Step 4: Field experimentation. This step aimed to collect experimental data on work duration, costs, and yields, in addition to ecological data, to (1) describe the performances of new AE activities, (2) measure and compare performances with the current farming system using the set of indicators, (3) improve their performances through continuous participatory assessments and optimization, and (4) study their impacts at

the regional scale with exploratory scenarios. This data collection has to be pursued in the long run (10 years).

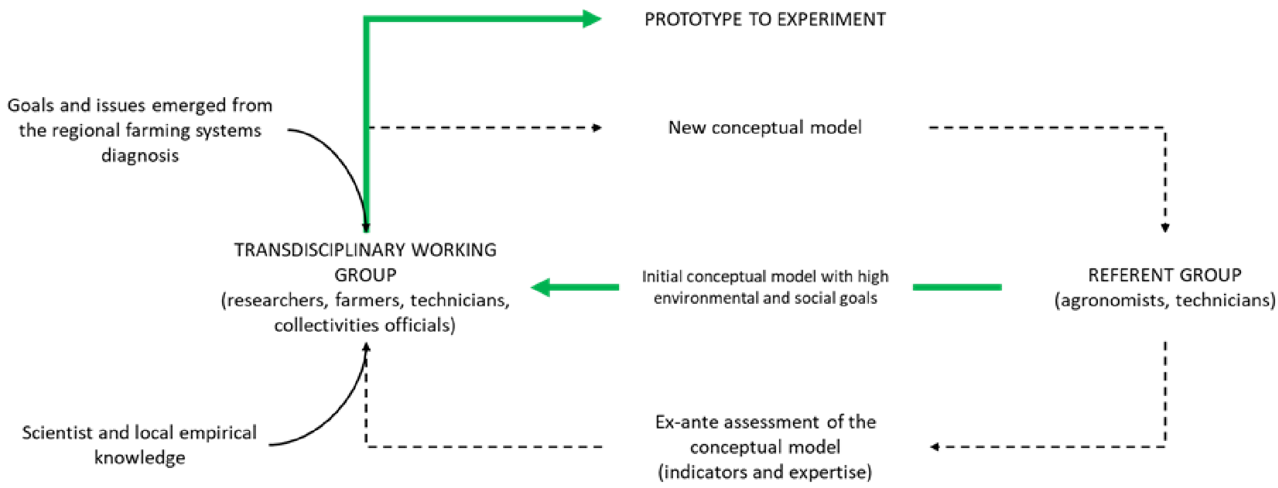

Figure 1. Progress of the farming system design (step 3). This co-design framework was aimed at developing the conceptual model of a climate-smart microfarm using AE principles/practices (solid arrows: Integration of tools and data, dashed arrows: iterative improvement, green arrow: initial and final prototypes).

2.3. Focus on the Co-Design Method (Step 3)

The current diversity of farming systems found in the AER (Figure S1) was used as a starting point for the design of the conceptual model. The design was guided by the different objectives and constraints arising from the assessment of the regional farming system, i.e., the improvement of the indicators while taking into account biophysical conditions and the socioeconomic context. One of the main objectives was to increase biodiversity, improve nutritional performance, reduce vulnerability, reduce emissions of greenhouse gases (GHG), and maintain an acceptable level of complexity and adoption using a combination of the crops currently managed in the AER.

The initial conceptual model of the AEMF was designed by the referent group based on the regional farming systems typology and diagnosis. It is characterized by high environmental and social goals but also relys exclusively on ecosystem services and the use of local inputs. This de novo design was based on AE principles and practices related to (1) soil and nutrient management, (2) flows of solar radiation, air, and water, (3) pest and disease management, (4) species and genetic diversification and (5) integrated farms (Table 1) guiding design choices were developed in few studies [40,41]. The potential benefits of most of those principles and practices were combined and compared with existing traditional practices carried out by local farmers involved in the design step. The characteristics and availability at the regional scale of most residual biomasses for their optimal use in farm processes were analyzed and debated. Conversely, production strategies and farm processes were defined with the aim of upgrading the most available residual biomass and supplying the most requested food. We validated the initial conceptual AEMF corresponding to the precise description of the farm structure and management. The ex-ante assessment was made with indicators on yields, work times, input prices and GHG emissions from peer-reviewed articles, grey literature, and expert knowledge.

Table 1. List of agro-ecological practices defined during the co-design step and applied on the AEMF.

Agro-Ecological Practices	Interest
Gravity drip irrigation, water harvesting	Water and energy use efficiency. With a rainfall of 2300 mm.yr^{-1} and 40 m^2 of rooftop, an average of 90 m^3 of water can be harvested each year on the AEMF and used through low-pressure drip irrigation [42].
Grass and ramial chipped wood (RCW) pathways	Permanent pathways dedicated to human and machinery traffic (associated with permanent crop seedbeds) allow for limiting erosion and reducing soil compaction and/or disruption, which are good ways toward soil structure improvement [43]. Moreover, *Poacea* on the pathways are P-acquisition-efficient species [44] mowed and used for composting. Permanent pathways are also important for the improvement of working conditions. On the AEMF, approximately 20% of the area was specifically dedicated to pathways and traffic.
Hedges	Windbreaks for wind-speed reduction, biomass production, biodiversity increase, leaching and erosion reduction, etc. [45]. Windbreaks could also reduce weed intrusion by tillering (assumption).
Increase biodiversity	An increase in biodiversity (cultivated and noncultivated) can improve the resilience of production systems [19,46] and contribute to limiting biodiversity erosion. More than 30 different species were managed on the AEMF.
Introduction of animal husbandry	Valorization of co-products, valorization of fallows, hastening recycling of biomass through manure production, etc. [47]. On the AEMF, we designed the Pasture and the Market gardening activities for easier interactions (manure management and rotation between both activities in the long term). When forage comes from external sources, livestock can contribute to nutrient inflow.
Introduction of adapted and native plants	Diversity conservation, adaptation, social interest. We selected species and cultivars according to their ability to cope with the local environment. For example, *Dioscorea* spp. and *Passiflorae* spp. are less sensitive to the ant *A. octospinosus*, Musa spp. is less sensitive to the fungus *M. fijiensis,* Solanum spp. is less sensitive to the bacteria *R. Solanacearum*, or *S. torvum* as rootstock for improving drought and pest tolerance of some *Solanaceae* production [48], etc.
Introduction of pest-repelling and trap plants	Decrease pest occurrences with the introduction of repelling plants in between cash crops and trap plants in surrounding areas based on the "push-pull" approach [49] and other studies such as [50], although other physical arrangements can be laid out [51]. This is a strategy for increasing biodiversity while targeting specific services. On the AEMF, we introduced plants with potential attractive effects on pests or their natural enemies (e.g., *P. purpureum*, *S. alata*) in the surrounding hedges and aromatic plants with potential repelling (e.g., *Plectranthus* spp., *Ocimum* spp., *Lippia* spp.) or nematicide effects (*Tagetes* spp.) in intercropped flower strips.
Massive use of compost	Soil structure, nutrients, and water availability [43,52,53]. The use of commercial compost and valorization of biomasses through on-farm composting are important strategies used on the AEMF. The field was amended with commercial compost (nutrients input) at a rate of 120 tFM.ha^{-1} (approximately 60 tDM.ha^{-1}), and then a specific amount of compost was added before each plantation. We based the rate of regular compost amendments during plantations (approximately 10 tDM.ha^{-1}.yr^{-1}) according to the recommendations for market gardening on ferralitic soils of the study region with the aim of balancing organic matter losses [54]. Compost amendment was one of the six main practices applied for nutrient management, i.e., compost amendment, legumes production, mulching, crop rotation (especially between pasture and market gardening), macerations of biofertilizers, and tree integration (biological pump). Apart from commercial compost and legumes, nutrient input also occurs through external biomass used for mulching or as forage, to a lesser extent.
Max. of solar radiation use (higher density, "understory")	Improvement of solar radiation use through higher-density planting or intercropping. Intercropping also allows for better efficiency through the valorization of different soil horizons. For example, we managed *Musa* spp. at low density but intercropped with other cash crops as a strategy to avoid propagation of *M. fijiensis*.
Minimum disturbance, reduce tillage	Improve stability of abiotic factors (temperature, humidity, soil structure) to favor soil fauna or beneficial insects (with slow reproduction cycles) and reduce erosion.
Permanent soil covering	Reduce weed infestation, soil compaction, and erosion; improve nutrient recycling and availability; and improve stability of abiotic factors. Cover crops also allow for the utilization of easily leached nutrients (especially N).

Table 1. *Cont.*

Agro-Ecological Practices	Interest
Production of biopesticides and biofertilizers	Improve yields, reduce pollution and increase autonomy. On the AEMF, we selected an important number of multipurpose plant species, and some of them can be used as biopesticides or biofertilizers, referred to as "bio-stimulants" according to the European legislation (https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000032472055/, accessed on 14 Febrary 2019), e.g., *Capsicum* spp., *C. papaya*.
Reuse of seeds	Management of (epi)-genetics factors [55], cost and availability of seeds. When legally possible, we selected seeds and seedlings produced on the AEMF for the next plantation.
Selective weeding	Increase synergy between weeding and biodiversity. This practice consisted of selecting and not removing a few weed species with beneficial effects or with low competitiveness (e.g., *C. juncea*, *P. oleracea*, *M. pudica*) during hand weeding. We applied this practice in some activities in order to manage patterns of spontaneous weed growth in the long term.
Use of agro-equipment (microequipment)	Improve efficiency and working conditions and reduce soil compaction. We designed the AEMF (pathways and rows-interows dimensions) in order to allow circulation and use of the microequipment (particularly, a small compact tractor).
Use of legumes	Nitrogen fixation through legume production [56]. On the AEMF, we introduced a large variety of legumes in crop rotations or as hedges (e.g., *V. unguiculata*, *C. ensiformis*, *C. Cajun*, *G. sepium*).

Globally, the interdisciplinary working group (researchers from different disciplines, i.e., agronomists, ecologists, botanists, economists, and technicians of the institute; farmers, i.e., the 12 farmers of the survey; and one collectivity official, i.e., a political leader of agricultural policy in the administrative division) put new strategies forward seeking to improve the initial model of AEMF through "Substitution" and "Efficiency" approaches while placing more emphasis on economic and management complexity aspects. Provisional conceptual models were evaluated by the referent group (ex-ante assessment) and presented as a new starting point for the next workshop (Figure 1). The first prototype to be developed had to integrate the maximum amount of scientific and local AE knowledge.

The issue of the nonuse of synthetic fertilizers and pesticides for the first prototype was also settled, not because of a dogmatic position but because the framework included an iterative and in itinere improvement of the experimental AEMF, which allows for ad hoc adaptation with regard to the provisional results. Adoption constraints were taken into account at field and farm levels. At a regional level, some constraints were taken into account as compost availability or food requirement, but the working group rather debated the possible bioeconomic, social, and environmental impacts and opportunities that could emerge from farm-scale choices. For example, forest managers of the study region look for professionals interested in cutting wood species with low economic value and bamboo (*B. vulgaris*) in order to both help manage the forest and value local biomasses. This situation led to debates about opportunities to value these biomasses in farm infrastructures or about strategies to improve the durability of some types of wood and bamboo.

After six months and twelve workshops, the first soil ploughing and compost amendment was performed in late 2017, and implementation of the AEMF called KARUSMART started in February 2018.

2.4. Experimentation and Data Acquisition (Step 4)

2.4.1. Technico-Economic Data

From the first ploughing, each action related to farm management was recorded in a database in terms of work times, costs, and yields, but also complexity and drudgery. In doing so, we obtained technical-economic data during the first two years of management. Those data were used for the first assessment of the farm using the 19 indicators of climate-smart agriculture (Table S1). For data collected at least two times during this period, the latest values obtained were used for the calculation of the indicators. For two agricultural activities management (poultry and some perennial crops: Lime *Citrus aurantifolia, Moringa Moringa oleifera* and Avocado *Persea americana*), which were not yet in full production, data obtained from local or peer-reviewed literature dealing with organic production systems was included to complete them.

2.4.2. Soil Analyses

The objective was to initiate the study of the evolution of four soil parameters in the long term (i.e., of at least 10 years): pH_{H2O}, pH_{KCl} (from soil samples using a benchtop pH meter), soil organic C (using a C analyzer after acidic removal of carbonates) and N (Total Kjeldahl Nitrogen method). The plan was to study those parameters not for fertilization scheme purposes but for the assessment of soil quality evolution in the long term. Soil organic C (SOC) and N (SON) allowed for the calculation of the C/N ratio, which is relevant to the breakdown of organic materials in the soil and is especially applicable in discussing the rate of breakdown of crop residues and their effects on levels of available soil nitrogen.

The first soil analysis was performed before the beginning of the farm implementation in February 2018. The sampling pattern consisted of the subdivision of the experimental field into six areas of approximately 0.1 ha. Six subsamples were taken at depths of 0–20 cm and 20–40 cm for each area. At this time, three soil analyses were performed: one in late 2017 (just before the farm implementation), one in 2019 (one year later), and one in 2022 (four years later). In this paper, those three soil analyses are presented as the first three points of a long-term series. However, long-term projections of SOC evolution were also presented with the indicator "SOC variation," provided by the model MORGWANIK [37] and based on the soil C value of the first year and a 30-year simulation period.

3. Results

3.1. Structure and Management of the AEMF

Figure 2 presented an overview of the structure of the AEMF as defined during the co-design process and implemented as a first prototype in the experimental field of the research institute. The prototype was designed with six different activities (Sugarcane, Banana, Tuber, Caribs, Pasture, and Market gardening), presenting a high level of diversity. The main productions of each activity corresponded to crops currently produced by the farmers of the study region (i.e., sugarcane, banana, yam, pineapple, tomato), while local breed sheep husbandry (also found in the region) was the choice to replace cows in this small-scaled production system with regard to its food regime and disease resistance.

The entire experimental field received an important amount of 120 tFM/ha of commercial compost (produced in the archipelago) as a long-term soil amendment. Only nutrient input based on commercial compost amendments and legume production (and, to a lesser extent, external biomass used as livestock forage and mulch) was used. Moreover, nutrient management relied on on-farm compost production (compost amended during plantation on a regular basis mainly produced on the farm), green manure, mulching, crop rotation (especially between pasture and market gardening), macerations of biofertilizers, tree integration (biological pump) and reduced tillage.

An important grid of drainage canals connected to a pond crosses the AEMF to prevent the high risk of flooding in the study region. Moreover, two different hedges (Hedges one and two) composed of multipurpose trees and aromatic and medicinal plants surrounded the whole farm. Hedge one (located downwind) includes trap plants, while the Market gardening and Tuber activities include permanent flower strips composed of medicinal and aromatic pest-repelling plants (Figure 2). Figure 3A presents the corresponding aerial photograph of the AEMF with illustrations of the different activities in Figure 3B–G. The broad pathways, the building, the pond, the drainage canals, both hedges, and some trees inside the AEMF were scheduled to remain in the same place, while a rotation of the six activities after ten years was planned, which will match with the massive compost amendment planned once every ten years.

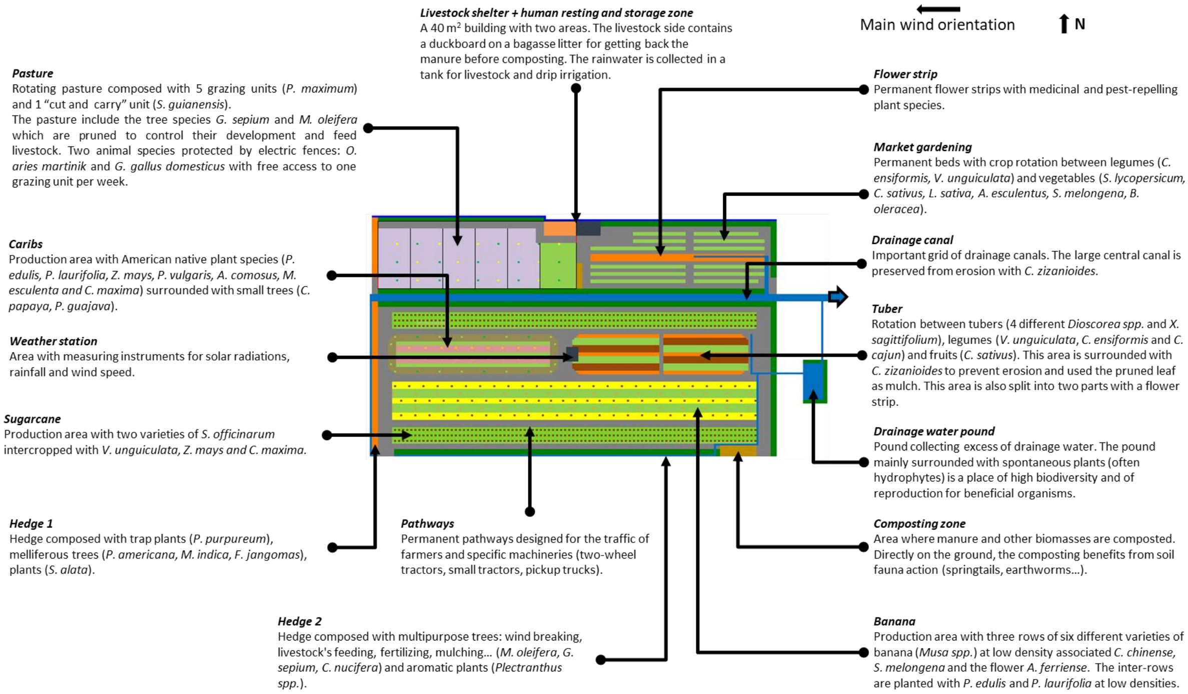

Figure 2. Overview of the AEMF structure experimented at the research institute.

3.2. Soil Analyses

Table 2 shows the results of the first three soil analyses carried out in late 2017 (just before the implementation of the AEMF) and then in 2019 and 2022 (one and four years later). For the 2017 sample, the pH_{H2O} was 5.2 and 5.1 at 0–20 cm and 20–40 cm, respectively. These values correspond to strongly acidic soils with low availability of certain nutrients, especially phosphorus, magnesium, and calcium [57,58]. In 2019, the pH_{H2O} increased by +18% from 5.2 to 6.1 at the 0–20 cm depth, shifting from a strong to moderately acidic soil. This trend continued in 2022 with a value of 6.5. At 20–40 cm depth, the pH increased slower in 2019, with a value of 5.2. The increase was stronger in 2022, with a value of 5.6, but the overall increase between 2017 and 2022 remained lower than that for the upper horizon. The effects of compost application on soil pH can be different from one situation to another depending on the initial soil pH, soil type, compost characteristics, etc. Increases in soil pH were found in numerous studies in both pot and field experiments [53,59].

Table 2. Results of the three first soil analyses at 0–20 cm and 20–40 cm for the pH (H_2O), pH (KCl), total soil organic nitrogen (N) and organic carbon (C), and C/N ratio.

Depth (cm)	**0–20**				**20–40**			
Year	**2017**	**2019**	**2022**	***VAR (2017–2022)***	**2017**	**2019**	**2022**	***VAR (2017–2022)***
pH(H_2O)	5.2	6.1	6.5	*+25%*	5.1	5.2	5.6	*+10%*
pH(KCl)	4.3	5.3	5.6	*+30%*	4.2	4.4	4.8	*+14%*
N %DM	0.18	0.22	0.25	*+39%*	0.13	0.14	0.18	*+38%*
C %DM	2.1	2.5	2.9	*+38%*	1.5	1.6	2.0	*+33%*
C/N	11.7	11.3	11.5	*−1.7%*	11.5	11.1	11.4	*−0.9%*

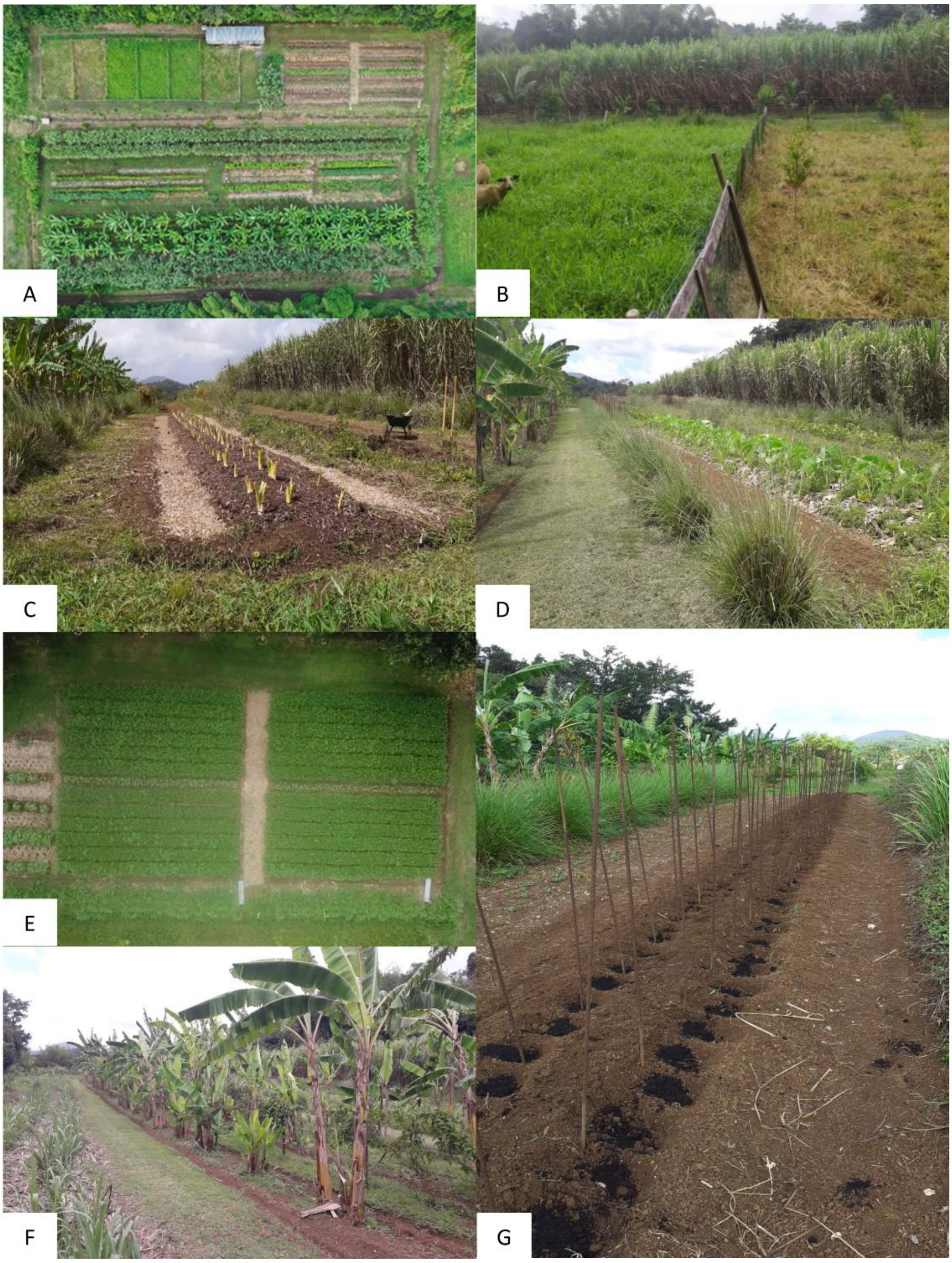

Figure 3. Aerial photographs of the AEMF. (**A**) The overview of the AEMF corresponds to the structure is presented in Figure 2. (**B**) The rotating pasture with on the right a unit after 7 days of grazing and on the left the sheep grazing on the next unit. (**C**) The tuber activity just after the plantation of *Xanthosoma sagittifolium*. (**D**) *X. sagittifolium* a few weeks after plantation. (**E**) Aerial photograph of the market gardening activity showing a high-density legumes plantation. (**F**) Photographs were taken between the banana and the sugarcane (a few weeks after harvesting) activities on the right and the left, respectively. Between both, an example of a permanent pathway is seen. (**G**) The tuber activity just before *Dioscorea* spp. plantation is an example of compost amendment. On the left, we can see *Chrysopogon zizanioides*, and on the right, a part of the permanent strip flower.

In 2017, the pH_{KCl} values were 4.3 and 4.2 at 0–20 cm and 20–40 cm depths, respectively, indicating the presence of exchangeable aluminum with potential toxicity [60]. For the 2019 sampling, the pH_{KCl} increased by +25% at the 0–20 cm depth from 4.3 to 5.3, indicating that aluminum was not a concern. However, aluminum toxicity remained a major constraint in the 20–40 cm horizon, indicated by a pH_{KCl} of 4.4 (+4%). This trend continued in 2022, with pH_{KCl} reaching values of 5.6 (+30%) and 4.8 (+14%) at 0–20 cm and 20–40 cm, respectively.

The SON analyses gave values of 0.18% and 0.13% at the 0–20 cm and 20–40 cm depths, respectively, for 2017. These results can be interpreted as medium and low concentrations of SON [58]. In 2019, the second analysis gave values of 0.22% (+21%) and 0.14% (+8%) for the 0–20 cm and 20–40 cm depths, respectively. In 2022, the SON still increased with values of 0.25% (+39%) and 0.18 (+38%) at 0–20 cm and 20–40 cm depths, respectively. However, these trends slowed and accelerated at depths of 0–20 cm and 20–40 cm, respectively.

The SOC measures resulted in values of 2.1% (0–20 cm) and 1.5% (20–40 cm), and the subsequent values of the C/N ratio were 11.7 and 11.5, respectively, in 2017 (Table 2). The SOC values increased to 2.5% (+17%) and 1.6% (+4%), and then the C/N ratios slightly decreased to 11.3 (−3.4%) and 11.1 (−3.5%), respectively, in the 2019 analyses. In 2022, the trend continued with SOC values of 2.9% (+38%) and 2.0% (+33%) for the 0–20 cm and 20–40 cm depths, respectively. These results correspond to an average increase of 8% per year for both horizons. The SOC increase at 20–40 cm depth was stronger during the second period, 2019–2022; on the other hand, both C/N ratios slightly increased but seemed to remain globally stable. Although the C/N ratio alone is not a predictor of the soil organic matter mineralization rate and depends on the climate conditions, soil quality, microbial biomass, and vegetation cover [61], those values indicate that the soil organic matter mineralization rate is not limited or overstimulated [62].

3.3. First Assessment of the AEMF Based on Experimental Data

Table 3 shows the results of the 19 indicators calculated for the whole AEMF expressed per hectare. The last column shows the average results obtained for the current farming systems of the study region during steps one and two (Supplementary Materials).

Table 3. Results of the indicators for the AEMF using the data collected during the first two years of implementation. The results were compared with the average values obtained for the regional farming system (Supplementary Materials). Corresponds to 16.5 $/hr for the AEMF in the case of household labor.

	INDICATORS	UNIT/YEAR	AEMF	REGIONAL VALUES
FOOD SECURITY	Autonomy	%	62%	−20%
	Investment cost	$/ha	93.0×10^3	8.6×10^3
	Gross margin	$/ha	8.1×10^3	3.3×10^3
	Labor requirement	FTE/ha	0.7	0.1
	Labor productivity	$/hr	7.4	23.3
	Complex carb.	Pers./ha	6	1
	Simple carb.	Pers./ha	25	15
	Saturated lipids	Pers./ha	2	1
	Unsaturated lipids	Pers./ha	3	1
	Proteins	Pers./ha	4	1
	Average nut. perf.	*Pers./ha*	*8*	3
ADAPTATION	Climate potential impact	%	25%	28%
	Economic diversity	-	3.7	0.8
	Active ingredients	kg/ha	0	4.4
	Inorganic nitrogen	kg/ha	0	70
	Irrigation/rainfall	%	6%	6%
	%Renewable	%	42%	25%
MITIGATION	GHG emissions	tCO_{2eq}/ha	2.7	1.9
	SOC variation	tCO_{2eq}/ha	+3.8	−0.5
	GHG balance	tCO_{2eq}/ha	−1.1	+2.4
	Ploughing	Number/ha	0.9	0.8

3.3.1. Food Security Outcomes

The autonomy of the AEMF was 62%, i.e., the average farmer's income without subsidies represented 62% of the total income. For comparison, the farms of the study region presented an autonomy of −20%. However, the investment cost of the AEMF was 93.0×10^3 $/ha, while it was, on average 8.6×10^3 $/ha for the farmers in the study region. In terms of labor, the AEMF required 0.7 FTE/ha, while the current regional activities required an average of 0.1 FTE/ha, which is seven times less. The gross margin obtained on the AEMF after two years was 8.1×10^3 $/ha, while the average value found for the current farming system was 3.3×10^3 $/ha. For the last economic indicator of net labor productivity, the AEMF paid $7.4/hr, while the average value for the current farming system was $23.3/h.

In terms of nutritional performance, the AEMF could feed an average of 8 pers./ha with a well-balanced diet, with values ranging from 2 pers./ha to 25 pers./ha for saturated lipids and simple carbohydrates, respectively. For comparison, the current farming system could feed an average of 3 pers./ha, with values ranging from 1 pers./ha to 15 pers./ha for saturated lipids and simple carbohydrates, respectively.

3.3.2. Adaptation Outcomes

The indicator of potential climate impact gave a value of 25% for the AEMF. According to the calculation method, this value means that current climate hazards potentially induce 25% of the maximum damages from which the farm could recover. At the regional scale, the potential impact of climate hazards on the current farming systems reached 28% on average. The economic diversity obtained for the AEMF, based on the Shannon index applied to the different gross margins of the system, was 3.7, while the current farming system relied on a very low economic diversity of 0.8. Both indicators of active pesticide ingredients and inorganic nitrogen gave the value of 0 kg/ha for the AEMF. In contrast, the current farming system requires an average of 4.4 kg/ha of active pesticide ingredients and 70 kg/ha of inorganic nitrogen. In terms of water use, both the AEMF and the farms of the study region put low pressure on water resources according to the "Irrigation/rainfall" indicator, with values of 6% and 8%, respectively. Those values correspond to the percentage of water drawn on the irrigation grid with regard to the total amount of rainfall on the farm area. Globally, 42% of the energy flow supporting AEMF production was renewable, while the current farming system relied on 25% of renewable energy, on average.

3.3.3. Mitigation Outcomes

The AEMF emitted 2.7 tCO_{2eq}/ha through its production system and sequestered +3.8 tCO_{2eq}/ha through soil management. The GHG balance obtained as the subtraction of the SOC variation from the GHG emissions gave a negative value of −1.1 tCO_{2eq}/ha for the AEMF, meaning that globally, this production system sequestered the equivalent of 1.1 tons of CO_2 per hectare each year. In contrast, the GHG balance of the current farming system was +2.4 tCO_{2eq}/ha on average, with values of 1.9 tCO_{2eq}/ha and −0.5 tCO_{2eq}/ha for both GHG emissions and SOC variation, respectively. It should be noted that, according to the calculation method, the GHG emissions indicator takes into account energy flows until the farm products reach the first client of the distribution chain. For example, in the case of the AEMF, we transported a part of the banana production from the farm to small markets of resellers or sugarcane to the distillery. Although many products can be sold onsite, some distributions are necessary due to the volume of production, especially for bananas and sugarcane. The ploughing intensity obtained for the AEMF gave a value of 0.9 ploughing/ha on average. For comparison, the farms of the study region required an average of 0.8 ploughing/ha due to the importance of sugarcane as a perennial crop requiring little soil ploughing.

4. Discussion

The agroecological microfarm (AEMF) implemented on 0.7 ha is the result of co-design between different stakeholders of the study region of North Basse-Terre (Guadeloupe). As presented in this paper, this production system relies exclusively on the integration of an important number of agroecological (AE) principles and practices (Table 1).

The soil analyses showed a strong impact of farm management on the four parameters studied. Both the soil pH_{H2O} and pH_{KCl} were significantly improved at 0–20 cm, shifting from 5.2 to 6.5 and from 4.3 to 5.6, respectively, after four years. The value of 6.5 for pH_{H2O} is a general target value, particularly for better availability of phosphorus [63], and the increase in pH_{KCl} indicated both lower exchangeable aluminum and soil acidity potential [60]. However, this increase was much lower at the 20–40 cm horizon for both pH_{H2O} and pH_{KCl}, remaining at concern values for most crops but still showing significant improvements. These trends should be studied over the long term because of the different temporalities of the agricultural practices and their effects, but the intermediary results currently contribute to the improvement of crop yield on the AEMF. Similar results on soil pH improvement obtained following compost application are documented [53,59] and will also be studied over the long term.

As for the soil pH values, the SOC variations showed higher increases for the 0–20 cm horizon. The annual increase in SOC for both horizons was very high, with an average of 8% yr^{-1} between 2017 and 2022, which was approximately 20 times higher than the 4 per 1000 project objective [64]. Similar effects of high applications of compost were found in other studies [65,66]. The SON variations were also in agreement with other studies [53]; these results were due to compost amendments and green manure production. The SON increase was stronger in the upper horizon during the first period. The increase differences between 0–20 cm and 20–40 cm were reduced during the second period, 2019–2022, for the four parameters. The main hypotheses that can be put forward are the superficial depth of soil management and the low mixing of the upper and lower horizons by macrofauna. Finally, according to the slight decrease in the C/N ratio, the adoption of the AE principles and practices potentially improved the soil conditions for better nitrogen availability. The objective will be to study how these first sharp variations and improvements in soil parameters will evolve during the next few years with regard to global soil management.

As synthesized in Figure 4, the indicators of food security showed promising results for the AEMF compared to current farming systems. First, the production system could pay out 0.7 FTE/ha of labor at the minimum wage while generating a gross margin of 8.3×10^3 \$/ha, corresponding to net productivity of \$7.4/h. Therefore, in cases where labor is carried out by the household, which is common in microfarms [35], the system could pay the farmer approximately \$7.4 more than the minimum hourly wage (i.e., \$9.1 in France for a total of \$16.5). In contrast, the value of 0.1 FTE/ha for the current farming system does not allow significant household labor capacities. Although the net labor productivity is much lower than for the current farming system, the AEMF would contribute far more to regional employment, in addition to a significant improvement in farmers' autonomy. However, although the economic results are socially acceptable, the low workforce availability in the agricultural sector, as well as the part-time farming of most participants in the study region, could remain a constraint for the adoption of such labor-intensive systems. It is also important to note that most productions of the AEMF were sold at 20% higher prices than conventional products observed on the food market.

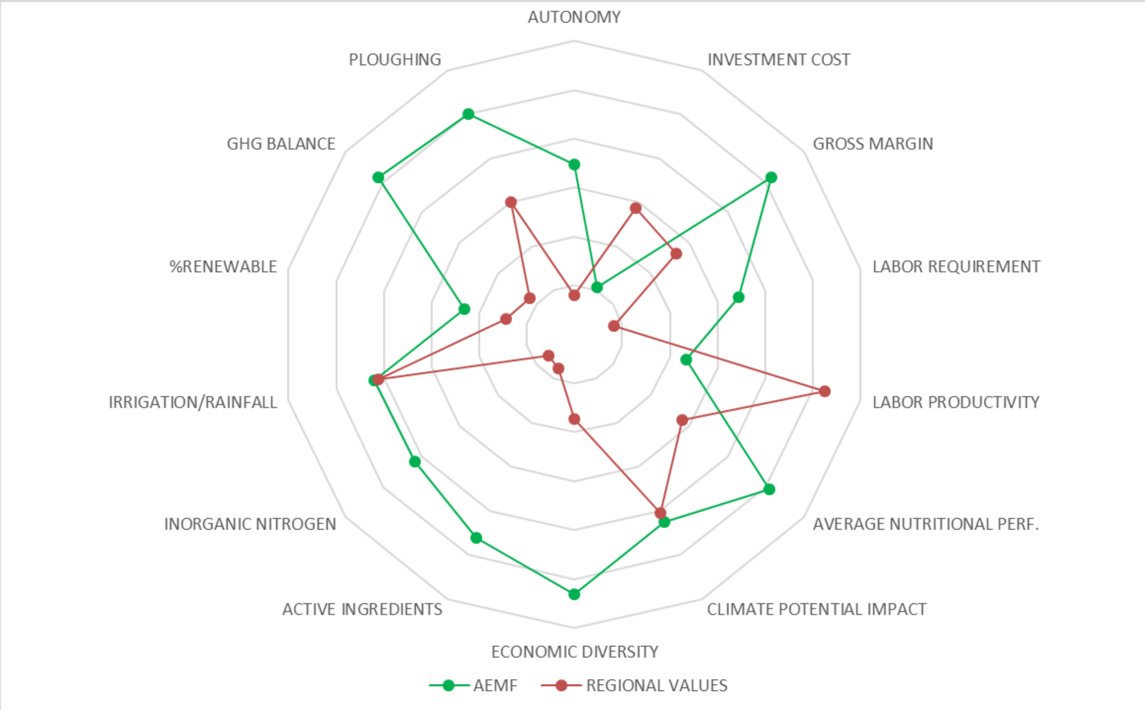

Figure 4. Synthetic view of the relative scores of the indicators for both the AEMF and the average regional farming system. Note: After mean-centering the scores, we multiplied the values of indicators that should have decreased (Investment cost, Climate potential impact, Active ingredients, Inorganic nitrogen, Irrigation/rainfall, GHG Balance, and Ploughing) by −1 in order to have the same reading. Higher values correspond to better performances.

Another constraint could be the average investment cost of the current activities, which is more than 10 times lower than for AEMF. The high investment cost for the AEMF was mainly due to the acquisition of a personal compact tractor and pick-up for transport, which could be overcome with the development of cooperatives for the use of agricultural equipment. The average farm acreage of the study region was 5.9 ha compared to the 0.7 ha of the AEMF prototype, which is 8.5 times smaller. Nonetheless, the results showed that the AEMF could feed 2.7 more people than the average current activities dominated by conventional sugarcane production (Table 3). This huge improvement, together with the important contribution to employment, could be a strong argument for fostering a specific revision of the installation incentive for young farmers.

The indicator of potential climate impact for the AEMF was −11% lower than the average value found in the study region. According to the calculation method (Table S1), this better score was mainly due to the higher level of biodiversity and also the integration of numerous AE practices in farm management, which allows for a reduction in sensitivity with regard to climate hazards (Table 1). Moreover, the net improvement of the economic diversity also contributes to the resilience and adaptation capacity of the farm.

Also contributing to the adaptation pillar, both active ingredients and inorganic nitrogen indicators showed a lower reliance of the AEMF on external inputs (the assumption of both indicators is that synthetic inputs are mainly replaced with local organic amendments (participating in the bioeconomy), crop/livestock integration and biodiversity), indicating its higher level of integration and adaptation to the local environment. Both indicators also showed the lower potential impact of the AEMF on the ecosystems with regard to the current farms of the study region. Moreover, this lower environmental impact was highlighted with the measure of the renewable fraction of energy input, which was almost 70% higher in the case of the AEMF. In terms of adaptation to water availability, both the

AEMF and the current activities presented good performances, requiring a low amount of irrigation water with regard to the rainfall in the study region.

The mitigation potential of the experimental farm was more important for SOC sequestration than for GHG emissions avoidance (Table 3). Indeed, the GHG emissions of the AEMF were 42% higher than the average value of the current activities. This result was mainly due to the share of pasture activity within the AEMF and also to the fuel consumption required for the regular distribution of specific products. For example, bananas need to be sold rapidly after harvesting. Thus, large harvests have limited onsite selling options. This weak point could be overcome by improving the onsite distribution capacity, for example, with the introduction of a transformation process allowing for longer preservation of products. In addition, these results foster the exploration of onsite renewable energy production strategies during the design of conceptual models, such as the installation of solar panels and the choice of electrical machinery. Nonetheless, when comparing those outcomes, nutritional performance as weighting should also be taken into account. Typically, the GHG balance for the AEMF corresponded to -0.1 tCO_{2eq} per fed person (i.e., the storage of 0.1 tons of CO_2 equivalent per well-balanced nourished person), while the current farm emitted 0.8 tCO_{2eq} per fed person.

Globally, as highlighted in Figure 4, the AEMF is more sustainable and outperformed the average results of the current farming system for the pillars of CSA (food security, adaptation, and mitigation), except for both investment cost and net labor productivity.

5. Conclusions, Limitations, and Perspectives

The present study aimed at codesigning and experimenting with a climate-smart AEMF entirely based on agroecological principles and practices in the experimental field of a research institute. This framework relied on the cooperation between the research institute and stakeholders (farmers and decision-makers) in order to produce specific technical-economic data about this production system. The interactions during successive workshops were productive in terms of analyses and proposals, reflecting global enthusiasm with regard to the experimentation of a whole farm where high-risk practices and strong constraints could be experienced. Nonetheless, these workshops also showed the divergence of opinions when different solutions to identified constraints were proposed, relying more or less on economic, social, or environmental goals, especially when solutions were discussed at the territorial level with regard to bioeconomic issues. The goal of the referent group was to come to a decision on these divergences based on either the ex-ante evaluations or simple expertise.

The results of this study highlighted promising improvements in performance for the three pillars of climate-smart agriculture based on a set of 19 indicators. Moreover, it is assumed that these results could be expanded upon in the coming years through continuous improvement of the soil characteristics and management strategies based on participatory field assessments (this tendency is already observable). Nevertheless, four limiting points are highlighted: (1) the investment cost of the system, (2) the amount of used fuel affecting the level of GHG emissions, (3) the labor requirement, which is beneficial at the global scale but makes the adoption of the prototype more difficult, and (4) net labor productivity.

The perspectives of this research are (1) to model with the collected field data and a regional bioeconomic model the potential of adoption of AEMFs and the impacts at the regional level on sustainability goals [67]; (2) to initiate discussions with decision-makers about the agroecological transition policy to implement (incentive allocations, communication, and training for farmers, development of eco-labeling, increase in land and workforce availability); and (3) develop cooperation with farmer's unions for implementing more AEMFs (especially targeting young farmers) and therefore obtaining more data on these systems. For now, this experimental AEMF has become the place for field participatory assessment and knowledge exchanges between stakeholders, students, and citizens and aims at pursuing long-term data collection.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture13010159/s1, Table S1: Short description of 11 indicators used for the diagnosis of farms with regard to the tree pillars of climate-smart agriculture; Figure S1: Typology of the farming systems found in the study region of the North Basse-Terre. References [68–77] are cited in supplementary materials.

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